Report of the NGST Near-Infrared Spectrometer Subcommittee

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Introduction

This subcommittee met in Hyannis and then held three telecons on October 11, October 18, and October 28. Not all members could participate in all events. We also formed a sub-group to define our best estimate of the appearance of the deep near-infrared sky, the “Design Reference Universe”. The results from the sub-group are attached as Appendix A. This sub-group performed an essential service because the optimum choice for spatial multiplexing for a near-infrared spectrometer depends strongly on the distributions of objects to be studied, and leads to a philosophical issue. We are attempting to choose a spectrometer design for a mission to be flown in 9 years and to choose a design for an instrument which will not begin to be built for at least two years. Part of the excitement for NGST lies in how much it will tell us about distant galaxies, and if we knew enough now to make a definitive selection of the very best near-infrared spectrometer type, some of this excitement would be gone. We also note that SIRTF will be launched in late 2001 and will make the first deep surveys at wavelengths longer than 2μm and could provide data which would influence the choice of near-infrared spectrometer for NGST.

The sub-committee is also concerned about choosing a spectrometer concept prematurely on other grounds. First, none of the ISIM studies could pursue designs deeply enough to determine all of the answers to critical questions such as the likely levels of scattered light within the proposed design nor could any of the designs be optimized to the point that definitive mass and volume numbers were produced. Second, some of the concepts proposed rely on micro-machined devices which have not yet been fully characterized or built into any spectrometer whatsoever. In the next two years these designs may become much more mature; a working groundbased instrument using a micro-mirror or micro-shutter array would make the selection of such a design much easier than it would be right now.
Last, although we could identify clear discriminators between Fourier transform and dispersive spectrometers, we found no simple discriminators between types of dispersive spectrometers with various puts and takes between concepts that are either very implementation dependent (e.g., scattered light) or tied to details of the exact observing program one wishes to execute (e.g., numbers of sources demanded per unit area at a given flux level).

We considered the following generic concepts:

1) Imaging Fourier transform spectrometer
2) Integral field spectrometer using an image slicer
3) MOS using mechanically positioned slits, with and without fibers
4) MOS using micro-mirror arrays
5) MOS using micro-shutters

Summary of Science Requirements leading to the proposed **concepts:**

The sub-committee identifies the following capabilities as being essential to carrying out the scientific goals of the NGST. In the opinion of the committee, all four are of great importance but they are presented here in decreasing order of priority: Furthermore, the gap between (a) and (b) is felt to be much smaller than between (b), (c), and (d), indeed (a) and (b) were perceived to be of approximately equal importance. A brief description of each capability is given with brief notes as to the science drivers in each case.

(a) *R=100 spatially-integrated spectroscopy at maximum sensitivity with multiplexing performance secondary.*

Several highly ranked proposals require maximum sensitivity at low resolution. These include the spectroscopic confirmation of photometrically estimated redshifts at the faintest possible levels. This is likely to be an essential part of the identification of the first luminous objects in the Universe at very high redshifts. Low-resolution spectroscopy is also involved in the detection of the signatures of re-ionization of the inter-galactic medium, and the spectroscopic follow-up of supernovae. While not explicitly identified in the DRM, we also see a need for low R identification spectroscopy of objects detected in other wavebands, e.g. faint radio, sub-mm, X-ray sources. In all of these R=100 programs, the target density (of the highest priority targets) is likely to be lowi (but probably much larger than 1 per square arc minute), and so the extremely high multiplexing gain that is possible at low spectral resolution is felt to be less important than maximizing the sensitivity. This also follows from the fact that R=100 spectroscopy will be background limited on the NGST, resulting in a maximum sensitivity gain over the ground.

In terms of simply detecting the faintest objects it should be noted that moderate resolution spectroscopy can go deeper than the continuum level detectable in broad-and images and emission-line searches may offer the deepest view of the very high redshift Universe (see Appendix B).

R=100 is likely to be adequate for brown dwarf and low-mass star spectroscopy, but this type of observation could require R as high as 300.

(b) *R=1000 spatially-integrated spectroscopy of multiple objects distributed over arcminute regions of sky with multiplexing performance paramount up to the expected number density of targets.*

The extragalactic science goal for highly multiplexed R=1000 spectroscopy is primarily the systematic characterization of the faint galaxy population (DRM 7). Emission line diagnostics of lines between 3500-7000 Å can be used to determine physical quantities such as reddening, star-formation rates, metallicities and the nature of photo-ionization sources (and at higher S/N, detailed measurements such as electron temperatures and densities etc.). A lower limit of R~500 for this work is set by the need to separate Hα and [NII]. Continuum measurements also yield information (with some degeneracy) about the ages and metallicities of the stellar populations. R=1000 spectroscopy also unambiguously establishes group membership (likely to be of critical importance in studies of the hierarchical assembly of galaxies and clusters) and to study the development of clustering in the spatial and velocity dimensions. Sensitivity to line emission is independent of resolution until the line is resolved which is unlikely to occur until R > 1000. Systems like the Local Group at high redshift will be spread over a few comoving Mpc (with the progenitor of a Milky Way Galaxy spread over 1 Mpc) and there is a need to characterize such environments as fully as possible by fully sampling all objects within these volumes. Many of the objects will be small, and the resolution is insufficient to reliably characterize the internal kinematics of galaxies, so spatial information is less important than high multiplexing gain, both on arcminute scales (to sample fully assembling cluster environments) and in building up large samples (to be sure of sampling representative volumes of the Universe). It is likely that photometric redshifts will be sufficiently reliable/accurate that they can be used to preselect objects. Reddening is required to interpret all optical/ultraviolet observations and the star-formation rate is a basic diagnostic of the evolutionary state of a galaxy. Likewise the metallicity gives an indication of the previous history of star-formation in an object and acts as a powerful constraint on the possible future descendants of objects seen at high redshift.

In the star-formation DRM, the driver for *R*=300-3000 spectroscopy is the characterization of large numbers of low-mass objects formed in star-formation clusters. The density of targets is high (at least as high as in the extragalactic case) but this looks operationally similar to the extragalactic program.

(c) *R=3000-5000 spatially-resolved 2-d spectroscopy at the diffraction limit of NGST of individual objects extended on the scales of a few arcsec.*

At higher resolution it is possible to study the internal kinematics of galaxies. Velocity measurements in the absence of spatial information are hard to interpret (especially for emission lines) and so the acquisition of spatial information is important for higher resolution spectroscopy. Because of the irregular morphologies of many of these objects, 2-d sampling is probably required. Mass measurements from kinematic data are extremely important in characterizing the hierarchical assembly of galaxies, and it is in terms of mass that our theoretical paradigm is described.

(d) *R=1000 spatially resolved spectroscopy and R=3000-5000 spatially integrated spectroscopy.*

At lower priority still is the capability to obtain the R=1000 diagnostic measurements across the face of an extended object (without significant kinematic information) or to obtain kinematic-level information without spatial information. The science drivers are as above.

All of the other (lower priority) NIR spectroscopy in the DRM is at resolutions $R > 10000$.

Generic Instrument Concepts mapped to ISIM Studies

Concept	ISIM Studies Discussing Concept
Imaging Fourier transform spectrometer	An Integral Field Infrared Spectrograph for the Next Generation Space Telescope An Imaging Fourier Transform Spectrometer for the NGST Bomem Final Report, Volumes 1-4 Conceptual Study of the NGST Science Instrument Module
Micro-mirror array spectrometer	NGST - MOS: A Multi-Object Spectrometer Using Micro Mirror Arrays Conceptual Study of the NGST Science Instrument Module
Micro-shutter array spectrometer	A Transmissive Mask Multi-Object Spectrometer Surface Micromachined Reconfigurable Multi-Slit Mask
Mechanically Positioned Slits	Canadian NGST NIR MOS/IFS Concept Study Conceptual Study of the NGST Science Instrument Module
Integral Field using image slicing	Integral Field / Multi-Object Spectrograph for the NGST Canadian NGST NIR MOS/IFS Concept Study A Solid Block Image Slicer for NGST

Overall ranking/importance of concepts

We have used the following criteria:

1) Ultimate point source sensitivity at R~100-1000. This implies modest undersampling of the PSF.

2) For R ~ 1000 and less, the need to cover the entire 1-5μm range for most objects although not necessarily simultaneously. For higher resolutions, a subset of the range is likely to be all that is required for a given object.

3) Ability to acquire multiple spectra at especially R~1000. DRM 7 drives this need most strongly. Acquiring spectra of adequate numbers of rare objects such as high-z AGN also drives the need for a large accessible field.

4) Resolutions of 3000 and higher are important but are most important at wavelengths longer than 2.5 microns where there is no competition from the ground. There is no need for multiple object spectroscopy at these resolutions..

5) At R~100-1000, spatial resolution is not as important as sensitivity while at R~3000 and greater, spatial resolution is important although the trade between full Nyquist sampling and somewhat lesser resolution needs to be made carefully.

We think that regardless of what type of multiple object or spatially resolved spectroscopy that NGST might be able to do, it must be able to get a spectrum of the faintest possible source. We have therefore given the highest weight to single object sensitivity.

The quantitative comparisons contained in the ISIM studies unequivocally show that, even with the detector background and read noise performances of presently available NIR detector arrays, dispersive spectrometers are capable of reaching significantly deeper than a Fourier transform spectrometer for a given integration time and spectral resolution. The reason for this is twofold. In the FTS each spectral element is subjected to the Poisson noise from the *integrated* sky background compared to the far smaller *dispersed* background of a conventional slit spectrograph. The FTS is also a scanning device and hence requires many more detector read-outs to build up a spectrum compared to a dispersive spectrograph. The already substantial single object sensitivity advantage of the dispersive approach over the FTS can only increase further as the noise characteristics of NIR detector arrays are further improved. Only a dispersive spectrograph can exploit these projected developments to the full.

Different dispersive spectrometer designs will yield somewhat varying point source sensitivities. For NGST, the biggest issue driving the relative sensitivity is the slit size -- use of an oversized slit or an integral field unit yields the best point source sensitivity. Because the backgrounds are so low on NGST and because the faintest sources are likely to be extremely small (<=0.1"), using a somewhat oversized slit would incur little or no penalty so we do not distinguish between types of dispersive spectrometers on the basis of point source sensitivity.

Examination of the various concepts for acquiring multiple spectra (as elaborated below) resulted in no clear winner now. A spectrometer for NGST will need to have exceptionally low levels of internal scattered light to take advantage of the low background. None of the concepts presented has ever been demonstrated to work at the required levels. The integral field and micro-mirror arrays may be most susceptible to this issue with mechanically positioned slits or micro-slit arrays being least susceptible. The different concepts also impose very different requirements on operations. The integral field units are the simplest while the MOS concepts all require some type of pre-existing image to guide the positioning of the field selectors. The concepts also have very different volume requirements with the MOS concepts generally being larger than integral field units. We note that a MOS with fibers has the potential to reduce the size of a MOS. Last, the MOS concepts can sample more field than the integral field units, but the integral field units have no restrictions on how close together sources are.

When we looked at the likely times to complete various observing programs, the dispersive spectrometers vary by perhaps as much as a factor of 4 or 5 in time in the most extreme cases. This range will not prevent any essential science from being achieved, and the real choice between concepts must be made when we know more about the likely real performance of the various devices. It is not at all clear now which type will deliver the most science for the lowest risk and lowest construction and operations costs.

Review of Spectrometer Types (key features): pros and cons of each concept

In the table below, we summarize the key features for the concepts considered. We have not distinguished between the various MOS concepts where they are essentially the same (e.g. for this table mechanical slits and micro-shutters are all "slits").

Parameter	IFTS	Integral Field	MOS/MMA	MOS/slits
Point source sensitivity	Poor	Excellent	Excellent	Excellent
Mapping speed	Excellent	Good	Good	Good
Areal coverage	Excellent	Good	Excellent	Excellent
Chance of Serendipity	Excellent	Excellent	Poor-Good	Poor-Good
Throughput	Good	Good	Good	Good
Volume/mass	Poor	Good	Poor	Poor-Good
Operational Risk	Medium -- needs a mechanism	Low -- may not require any mechanisms	Low- Medium -- may require a mechanism	Low- Medium -- may require mechanisms
Operational Complexity	Medium -- low accuracy on pointing but high data volume	Low	High -- requires autonomous positioning of slits	High -- requires autonomous positioning of slits, mechanical slits most complex
Spectral Resolution	Broad range and easily changed	Fixed by design	Can be changed with grating selector	Can be changed with grating selector

Summary findings and recommendations:

1) For any spectral resolution, a dispersive spectrometer will provide better sensitivity on a single point source than a Fourier transform spectrometer.

2) In the case of acquiring spectra of every point on the sky in a given field of view, an imaging FTS has a speed advantage over dispersive spectrometers that increases with spectral resolution assuming that detectors have no better performance than from a few months ago. We want to choose a spectrometer that can yield the ultimate performance using the detectors which will be available in several years. We also note that at the higher resolutions where the speed difference is greatest now, we do not see a need for spectra of every point on the sky. Therefore we confirm the statement that we made in Hyannis that an IFTS will not be the sole near-infrared spectrometer of choice for NGST.

3) We do think that an IFTS might be effective in a low spectral resolution camera and urge careful examination of its use in this application. We would assume that since it would be used at low resolution only, it would need only a relatively small mirror travel and would not need to be as large as an instrument intended to be the higher resolution spectrometer.

4) Most of the time in the DRM is spent at R~1000. Improvements in detector and readout electronics appear potentially able to provide zodiacal background limited performance at this resolution, and we strongly suggest that work be continued in this area.

5) Because we find R~100-200 and R~1000 spectroscopy essential and R~3000-5000 highly desirable, further investigation of schemes to include a range of 10-30 in spectral resolution in one instrument package should be studied more thoroughly. In addition, the volume required for R~1000 spatially multiplexed spectroscopy needs to be studied more thoroughly -- Appendix A implies that with an exposure time of 10^5 seconds, a 1’x1’ field will contain ~200 “interesting” galaxies where “interesting” means z>3.

6) The ASWG has already rated DRM programs using R~10000 and higher as of lesser importance scientifically. We note that for $\lambda<2.5\mu m$, the ground becomes competitive at high resolutions. Last, no ISIM study proposing such resolutions was submitted. Therefore we are not recommending such a spectrometer.

We therefore recommend the following suite of capabilities using dispersive spectrometers:

1) R~150 spectrometer optimized for point source sensitivity with spatial resolution and multiple object capability of secondary importance.
2) R~1000 spectrometer optimized for both sensitivity and multiple object capability. Spatial resolution is of secondary importance.
3) Spatially-resolved spectroscopy at R~4000 over at least 2”in length and with good but not necessarily Nyquist sampling of the Airy pattern.

Capability 3) could be provided by either a long-slit or an integral field unit with the long-slit being simpler to produce but the integral field being easier to operate.

The most difficult choice facing the Near-Infrared Spectrometer committee is the one of which type of dispersive instrument should be constructed to provide capabilities 1) and especially 2), namely an integral field unit versus an MOS. If all possibilities could remain on the table until two years from now when the U.S. instruments will be selected, we would urge that no selection be made now. There are currently too many performance unknowns and uncertainty in the character of the high redshift Universe that a choice now might not be the correct one then. The prospects for detector improvements also support waiting to make a choice. If we must choose between these dispersive concepts now so that the agreements between all of the NGST partners can be kept, we then make the following observations. DRM 7 appears to be most easily done with a MOS rather than an integral field unit because of the expected number density of faint galaxies with the caveat that this is a case where our lack of knowledge of the deep sky is most important. R~1000 spectroscopy of galaxy clusters is another example which also requires accessibility to fields larger than an arc minute for efficient observing. Other programs where field accessibility is an issue include supernovae, gravitational lenses, and rare objects such as high-z AGN. An integral field unit might not be so well matched to the number density of faint galaxies but would be better optimized for some other projects. The committee did not come to closure on exactly how much field must be accessible at one time and how much could be done by sequential observing. If we examine the state of MOS designs now, only mechanically positionable slits have been used on the ground. None of these spectrometers use cryogenic positioners to the best of our knowledge. On the other hand, cryogenic integral field units have been built, but none have been operated at backgrounds anywhere near as low as NGST’s. The ASWG would have to choose between an IFU and mechanical slits if we must choose now.

If the choice can be postponed, then we urge the NGST project to invest in prototypes using image slicers, near-infrared fibers, micro-mirror arrays, and micro-shutters. Measurement of scattered light for all concepts is needed. Infrared fibers have not been demonstrated over the entire 1-5μm range nor have they been shown to be robust enough for space use. Neither micro-mirror arrays nor micro-shutters have been demonstrated in any type of spectrograph. In this case, a demonstration of spectrometer performance and software that could autonomously configure the selection elements from an input image would be crucial.

Appendix A: The Design Reference Universe, Version 4

Numbers in units of objects per sq. arcmin.

GALAXIES:

Numbers relevant for continuum detection at
R ~ 100 in 10^6 s with dispersive spectrograph:

820	Galaxies brighter than K_AB = 29
621	z < 3
119	z = 3-5

74 z = 5-10
5 z > 10
0 Galaxies with r > 0.3" within K_AB=28-29

Numbers relevant for R ~ 100 in 10^5 s (continuum):

396 Galaxies brighter than K_AB = 27.5
324 z < 3
53 z = 3-5
17 z = 5-10
0.4 z > 10
1 Galaxies with r > 0.3"

Numbers relevant for R ~ 300 in 10^5 s (continuum):

242 Galaxies brighter than K_AB = 26.5
210 z < 3
26 z = 3-5
6 z = 5-10
0 z > 10
3 Galaxies with r > 0.3"

Numbers relevant for R ~ 1000 in 10^5 s (continuum):

145 Galaxies brighter than K_AB = 25.5
132 z < 3
11.5 z = 3-5
1.7 z = 5-10
0 z > 10
1 with z > 3 and circular velocity > 150 km/s
6 Galaxies with r > 0.3"

Numbers relevant for R ~ 3000 in 10^5 s (continuum):

85 Galaxies brighter than K_AB = 24.5 (R~3000)
80 z < 3
5 z = 3-5
0.26 z = 5-10
0 z > 10
0.2 with z > 3 and circular velocity > 50 km/s
9 Galaxies with r > 0.3"

EMISSION LINES

H-α -- numbers detectable at R~100 to R~1000 (i.e. unresolved,
detector-noise limited) in 10^5 s
1250 galaxies arcmin-2 with H-α above Kennicutt mean
940 z < 3 (assumes 75%)
181 z = 3-5 (assumes 14.5%)
56 z = 5-7 (assumes 4.5%)

Lyman-α -- (these numbers may need to be revised upwards)

57 Galaxies with f(Lyα) > 1.5e-19 erg cm^{-2} s^{-1} and EW(rest)>100Å
43 z < 3

8 z = 3-5
5 z = 5-10
0.3 z > 10

SUPERNOVAE

1.5 SNe Ia with K_AB < 29 (R~ 100 in 10^6 s)
0.6 SNe Ia with K_AB < 27.5 (R~ 100 in 10^5 s)
0.3 SNe II with K_AB < 29 (R~ 100 in 10^6 s)
0.1 SNe II with K_AB < 27.5 (R~ 100 in 10^5 s)

AGN
82 AGN brighter than K_AB = 29 (R~100 in 10^6 s)
z < 3
z = 3-5
4 z = 5-10
0.6 z > 10
39 AGN brighter than K_AB = 27.5 (R~100 in 10^5 s)
z < 3
z = 3-5
2.5 z = 5-10
0.006 z > 10
24 AGN brighter than K_AB = 26.5 (R~300)
z < 3
z = 3-5
2 z = 5-10
0 z > 10

STRONG GRAVITATIONAL LENSES

3 Lens systems brighter than K_AB = 29 (R~100 in 10^6 s)
0.3 z(lens) > 2
1 Lens systems brighter than K_AB = 27.5 (R~100 in 10^5 s)
0.1 z(lens) > 2
0.6 Lens systems brighter than K_AB = 26.5 (R~300)
0.06 z(lens) > 2
0.3 Lenses brighter than K_AB = 25.5 (R~1000 for kinematics)
0.03 z(lens) > 2

CLUSTERS

6.44e-3 Clusters more massive than 10^14 M_sol
1.50e-3 z > 1
9.80e-8 z > 3
0.477 Clusters more massive than 10^13 M_sol
0.289 z > 1
5.84e-3 z > 3

STARS

At North Ecliptic Pole (i.e. potential CVZ):
0.73 Stars brighter than K_AB = 16 (Guide stars)
11.7 Stars brighter than K_AB = 20? (Scattered light)
Scaled to Galactic Poles:
0.37 Stars brighter than K_AB = 16 (Guide stars)
5.8 Stars brighter than K_AB = 20? (Scattered light)

Notes:

Notes on design-reference universe

Number counts

Overall number counts are uncertain by a factor of ~2 at KAB ~ 25. The uncertainty grows to more than an order of magnitude at KAB = 34. The total number counts adopted are from Arribas (reference?) and bracket the values produced by the Gardner (reference) number counts model and the Ferguson (ARAA, in preparation) compilation of observed counts.

Using figure 3, right panel, of Lanzetta et al (astro-ph/9907281) we derive the following table, which gives the percentage of galaxies within each redshift bin as a function of their magnitudes,

K_ab	29	27.5	26.5	25.5	24.5
z < 3	0.758	0.820	0.866	0.909	0.937
3<z<5	0.145	0.133	0.108	0.079	0.060
5<z<10	0.090	0.044	0.025	0.012	0.003
z>10	0.006	0.001	0.000	0.000	0.000

These fractions are used to derive the numbers in different redshift intervals. At magnitudes K_AB > 29, the theoretical predictions from Haiman & Loeb (reference) give larger numbers. By K_AB = 34, the Haiman & Loeb prediction for galaxies at 5 < z < 10 exceeds our extrapolation for the total number counts. However brighter than K_AB = 27.5 the predictions are within a factor of **two?** the empirical redshift distributions we have adopted.

Numbers of galaxies with circular velocities above some value come from Benson & Frenk (below).

The numbers of galaxies with r > 0.3" comes from the HDF-S NICMOS data. The value of "r" used is max(a,b) where a and b are the "RMS" values of the major and minor axes returned from SExtractor. This is probably a reasonable measure...galaxies with blobby linear morphologies can in principle end up with a big value of a or b and might be the best hope for resolved spectroscopy of faint objects (assuming of course they have bright emission lines, since they will too faint in the continuum for the magnitudes listed in the table). The actual measured numbers of galaxies in the different cuts in the HDF-S are:

H_AB	Number
27-28	1
26-27	4
25-26	12
24-25	9

The numbers in the table represent a smooth approximation to this, scaled to 1 square arcmin.

The number of H-alpha emission lines was computed as follows.

1) Assume that all high-z galaxies are dominated by star-formation
2) Assume that the continuum flux is given by the standard conversion from SFR to UV luminosity

$$L\_UV(\text{erg s}^{-1}\text{ Hz}^{-1}) = 8e27 * SFR\ (\text{m\_sol yr}^{-1})$$

3) Assume to first order these are flat-spectrum objects

$$f_\nu\ (H\alpha\_\text{continuum}) = f_\nu(UV)$$

4) Assume the H-α luminosity is given by the Kennicutt (1998) relation

L_H_{α} (erg s^{-1}) = 1.26e41 * SFR

This may be a bit on the optimistic side for the emission lines, since not all the continuum may be coming from star formation, and it is likely to be somewhat redder than flat-spectrum. But let's press on and calculate limiting sensitivities using the NMS and the Yardstick mission. For the sake of argument, put H-α at 4 microns (z=5) and consider the continuum there as well.

Continuum limiting flux (point source, R=5, S/N=5 in 10^5 s), from NMS exposure-time calculator:

0.68 nJy => AB = 31.8
=> 6.8e-33 erg s^{-1} Hz^{-1}

Continuum limiting flux at R=1000, (point source, S/N=5 in 10^5 s), from NMS

54.9 nJy => AB = 27.1
=> 1.0e-21 erg cm-2 s-1 A-1

Assume the line is unresolved. The continuum flux limit then translates into an emission-line flux limit of

1.0e-21 * δλ = 1.0e-21*(40Å) = 4.e-20 erg cm^{-2} s^{-1}

Now lets assume a luminosity-distance of D = 1.55e29 cm, and compute star-formation rates for both cases:

CONTINUUM: AB=31.8 @ z=5 => L = 2.05e27 erg s^{-1} Hz
=> SFR = 0.25 M_sol yr^{-1}

LINE: F=4.e-20 @ z=5 => L = 1.2e40 erg s^{-1}
SFR = 0.095 M_sol yr^{-1}

So the R=1000 spectrum can detect star-formation rates ~ 2.6 times lower than the R=5 continuum image can.

=> The appropriate continuum mag limit for detecting
H-α at R=1000, S/N = 5 in 10^5 s is AB=32.8.

To be a little conservative, we should probably divide the number-counts at this AB mag by ~2 to account for the caveats above, and the fact that (locally at least) half the emission-line galaxies scatter below the mean Kennicutt relation.

Extrapolating the K-band counts down to AB=32.8 is subject to about a factor of 10 error. A middle-of-the road estimate is 2500 galaxies $arcmin^{-2}$. Dividing these number counts by 2 to discard galaxies with weaker-than-average H-α, this gives the following middle-of-the road estimate for galaxies with detectable H-α:

1250 galaxies arcmin-2 with H-α above Kennicutt mean
940 z < 3 (assumes 75%)
181 z = 3-5 (assumes 14.5%)
56 z = 5-7 (assumes 4.5% -- from Arribas' z=5-10 estimate scaled by the relative volume z=5-7/z=5-10)

The number of Ly-α emission-line galaxies was computed assuming a constant fraction of the galaxy population at each z has EW(rest) > 100Å. The problem is deciding what that fraction is. For the moment we just pick 5%. Scaling from the ~200 U-band Ly-break galaxies in the HDF, that gives 2 Ly-α emitters per sq. arcmin (a factor of two lower than Hu et al, but in the same ballpark). The relevant continuum magnitude limit is K_AB ~ 31 for F(lim) ~ 1.5e-19, EW=100Å. Using our adopting redshift fractions at K=29 and multiplying by 1.4 to account for the deeper limit, then taking 5%, we get the numbers shown in the table. This is in the same ballpark as an estimate from the Haiman & Spaans (1999) model.

Supernova Reference: Dahlen & Fransson (1999, A&A 350, 349).

Lensing reference: Barkana & Loeb 1999 astro-ph/9906398. Based on their table 1, we have assumed the number of strongly lensed sources is ~ 2% of the z>3 population. (If you trust the paper, this is a very conservative estimate, as it ignores the lower redshift objects -- however it looks like this paper would overpredict the number of lenses in the HDF.) The number of systems with z(lens) > 2 is based on an eyeball integration of Barkana & Loeb fig. 2.

Stars: The NEP measurement at K<16 is an actual measurement of the field. The NGP and K<20 numbers are extrapolations.

Cluster numbers come from Benson & Frenk (below).

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For comparison, here are some counts from Andrew Benson
& Carlos Frenk, predicted via semi-analytic models.

GALAXIES:
2013.4 (6%) Galaxies brighter than K_AB = 29 (R~100 in 10^6 s)
1775.5 (7%) z < 3
231.2 z = 3-5
6.7 z = 5-10
0 z > 10
886.9 (2%) Galaxies brighter than K_AB = 27.5 (R~100 in 10^5 s)
849.5 (2%) z < 3
36.8 z = 3-5
0.5 z = 5-10
0 z > 10
465.3 Galaxies brighter than K_AB = 26.5 (R~300)
456.5 z < 3
8.7 z = 3-5
0.22 z = 5-10
0 z > 10
234.4 Galaxies brighter than K_AB = 25.5 (R~1000)
232.4 z < 3
1.9 z = 3-5
0.06 z = 5-10
0 z > 10
1.1 with z > 3 and circular velocity > 150 km/s
1.0 more extended than 1 arcsec at SB > mu(K_AB) < 25
112.5 Galaxies brighter than K_AB = 24.5 (R~3000)
112.0 z < 3
0.47 z = 3-5
0.03 z = 5-10
0 z > 10
0.18 with z > 3 and circular velocity > 50 km/s
1.0 more extended than 1 arcsec at SB > mu(K_AB) < 25
EMISSION LINES (!!!!!!!!THESE VALUES ARE QUITE UNCERTAIN - FURTHER
WORK BEING DONE ON THESE CALCULATIONS AS WE SPEAK!!!!!!!!!)
629.5 Objects with f(Halpha) > 1.0e-18 erg cm-2 s-1
540.2 z < 3

86.0	z = 3-5
3.2	z = 5-7

SUPERNOVAE

6.13	SNe II with K_AB < 29 (R~ 100 in 10^6 s)
2.00	SNe II with K_AB < 27.5 (R~ 100 in 10^5 s)

CLUSTERS

6.44e-3	Clusters more massive than 10^14 M_sol
1.50e-3	z > 1
9.80e-8	z > 3
0.477	Clusters more massive than 10^13 M_sol
0.289	z > 1
5.84e-3	z > 3

Notes:

>From Carlos Frenk:
I should emphasize that some of the results are rather uncertain, particularly those that pertain to extreme circumstances, either very high z (z>5) or very small galaxies (Vc < 50 km/s). Apart from uncertainties arising from the treatment of certain physical effects like ``feedback'' there are also uncertainties arising from the choice of IMF and, very importantly, from the treatment of dust extinction. Our prescription includes a plausible dust model, but we are currently testing it against observations such as the IRAS lum fn at low z and the SCUBA counts at high z. This is still work in progress.

The model does not yet include the effects of lensing, but this would be easy to remedy. However, we do not expect lensing to be any more important for deep NGST work than it is for the HDF since most of the big lenses lie at moderate redshifts (z<1). Finally, our model does not yet include AGN, but this too is something we can remedy -- there are several prescriptions around for identifying dark matter halos with AGN of a given luminosity. We are planning to work on this soon.

>From Andrew Benson:

I've filled in as much of the blanks in your "DRU" as I've been able to so far. All results are for our fiducial model which has a LambdaCDM cosmology (Omega0=0.3, Lambda0=0.7, h=0.7, sigma8=0.93, gamma=0.19, Omegab=0.02) and has the important feature that it describes the properties of local galaxies well. Below are some notes on the values:

Galaxies: I've been unable to provide a number for the counts to K_AB=34 as this requires modeling very small halos. This is possible in principle, but needs some refinements to our code to explore this region efficiently. For the brighter cuts, I've listed the required numbers. Where a value is given in brackets after the number, it gives the uncertainty in the quantity due to possible contributions from intrinsically faint, nearby galaxies which haven't been included in the model (again because the very smallest halos aren't simulated at the moment). I've only listed an error if it is greater than 1%.

Emission lines: I've listed values for the H-α line here (Lymanα will be possible but hasn't been coded into the model as yet). These numbers are still quite uncertain as the emission line properties are "work in progress".

Supernovae: Numbers listed for type II supernovae are derived from the total instantaneous star formation rate in the model plus the specified IMF (from Kennicutt 1983). I assume that each SNe II is seen as a 7000K black body which lasts for 80 days (this is the model of Miralda-Escude & Rees 1997).

Clusters: These numbers were calculated using the Press-Schechter theory on it own.

Appendix B: Note about emission line searches

For an unresolved emission line of relative equivalent width W ($=\delta\lambda/\lambda \sim 0.1$), the gain in limiting sensitivity of a spectrograph at resolution R compared with a broad band filter of resolution r is given in the background limited case by:

$$\frac{(S/N)_R}{(S/N)_r} = \frac{(W + R^{-1})}{(W + r^{-1})}\sqrt{\frac{R}{r}}$$

In the simple case of $r^{-1} >> W >> R^{1}$ (i.e. the flux in the spectrograph is dominated by the unresolved line, and in the filter by the continuum), this reduces to:

$$\frac{(S/N)_R}{(S/N)_r} = \frac{W}{r^{-1}}\sqrt{\frac{R}{r}} = W\sqrt{Rr}$$

So, for $W = 0.1$ (optimistically the case for un-extinguished Lyman a) and R=300 and r = 3, the gain is a factor of 3 (or over a magnitude in effective limiting apparent magnitude).